Building a Virtual Model of a Baleen Whale: Phase 2

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LONG-TERM GOALS

This project proposes to CT scan an entire baleen whale and, eventually, build a vibroacoustic model that will allow us to simulate how sound interacts with the whale's anatomy.

OBJECTIVES

The project has been subdivided into three phases. Phase 1 has been completed; we constructed the overall strategy and constructed a specialized bag that will be used to tow a dead whale to a boat haul-out facility. This project covers Phase 2, where the objectives are primarily technological. We will construct more basic equipment, conduct some tests, and prepare for an attempt to capture a whale carcass. The basic plan is to capture a postmortem California Gray Whale (*Eschrichtius robustus*) (Lilljeborg, 1861) after it dies along the annual migration route. The specimen will then be cooled, towed to a haul-out yard, placed in a specially designed container, and then transported to a commercial freezer. Eventually, the specimen will be transported to an industrial sized CT scanner. After the CT scans are conducted on the entire specimen the whale will be transported to the Smithsonian Institution where it will be taken apart so that the tissue properties can be measured. The CT scan data and tissue property measurements will be used to construct a finite element model in Phase 3, planned for a future proposal.

APPROACH

Key Personnel

- **Captain Jim Christmann**, RV Shana Rae and Monterey Canyon Research Vessels, Inc., Santa Cruz, CA.
- **Mr. David Jablonski,** Sanctuary Stainless, Moss Landing California.
- **Dr. David Casper (DVM),** Director, Long Marine Lab Marine Mammal Stranding Network, **University of California, Santa Cruz.**
- **Professor Petr Krysl,** Department of Engineering, University of California, San Diego.

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Justification: Oceanic sound levels, especially low-frequencies from geologic exploration, industrial development, shipping, and military activities, have increased steadily over the last half-century (McCarthy, 2005). Low frequency sounds have been known to negatively impact large whales (Frantzis, 1998; Balcomb and Claridge, 2001; Malakoff, 2002) and possibly many other living marine resources.

Short of experimentally exposing additional animals, which is always expensive, or can be immoral, and is often impossible, the most promising technique for discovering acoustic pathways and assessing potential effects from any particular sound, involves finite element modeling (FEM). The FEM method has been applied successfully to engineering problems over the past half century and is now in widespread use. In recent years, FEM techniques have been used in various bioacoustical and biomechanical applications (Müller, 2004; Ross, 2005).

Our team has pioneered a suite of techniques that combine the anatomic geometry obtained from CT scans (Cranford, 1988; Cranford *et al.*, 1996) with measurements of tissue elasticity (Soldevilla *et al.*, 2005; Hess *et al.*, 2006) and custom FEM software (Krysl *et al.*, 2006), the *vibroacoustic toolkit* (VATk). This combination produces a versatile computational environment for vibroacoustic simulations (Krysl *et al.*, 2008). This suite of techniques can also be used to assess acoustic exposure across a broad taxonomic spectrum.

The intellectual merit of these methods has been demonstrated by the recently published discovery of a new pathway for sound entering the head of a beaked whale (Cranford *et al.*, 2008a), a result that challenges the long accepted paradigm of toothed whale hearing (Norris, 1968). In addition, anatomic similarities with all living toothed whales suggest that this new pathway may also be the original pathway used by the ancient whales (archaeocetes) in the Eocene. This discovery was catalyzed by the disparate views and collective efforts of experts in different disciplines, the essence of our approach.

These computer-enabled investigative methods have already transformed our capacity to generate original knowledge and understand the bioacoustics of marine mammals (Cranford, 2000; Cranford and Amundin, 2003; Cranford *et al.*, 2008a; Cranford *et al.*, 2008b). The resulting simulations allow us to emulate, for example, the sound generation mechanism and the formation of an acoustic transmission beam, or to measure the amplitude differences and time delays for sounds reaching each of the ear complexes. These are just a few examples of the predictions and understanding we can glean from basic vibroacoustic simulations, *all of them from inside the organisms*.

Technical Concept: Toward the goal of freezing a baleen whale specimen for X-ray or CT scan analysis of soft anterior acoustic organs, we envision taking advantage of a freshly-reported (perhaps even as-it-happens) kill of a young Gray Whale by a Killer Whale (*Orcinus orca*), the often observed "Orca kill". The plan calls for using a whale that is less than 35 feet long, to best utilize existing overland highway width and weight limits, on the freshest specimen possible.

The Monterey Bay offers one of the best possible locales for this effort, with a small degree of protection from open-ocean conditions and a well-documented affinity for migrating Gray Whale cows with calves. There is also a cluster of three municipal foci of commercial whale-watching activities (Santa Cruz, Moss Landing, and Monterey) that can provide some passive, cost-free observational capabilities from their day-to-day efforts to monitor migration trends.

***Aerial Search Capability*:** We will also need a minor amount of aerial search support on this project. The needle in the haystack metaphor does seem apt for this enterprise, since every element of it will be influenced by the sea, an unpredictable partner in many instances. The aerial survey support is an important component to this project, and the amount of funding for that support is a very small percentage of the overall budget. Let us expand on our reasoning and intentions here.

What we are proposing a small number of aerial support hours (30 hours over four months each year, but *only on a few selected mornings of the most perfect weather conditions, which we can identify from short term forecasts*. For this work, we intend to hire Bob Van Wagenen at Ecoscan Resource Data in Watsonville, a veteran marine survey pilot with some 35 years of experience conducting aerial survey and census work for a wide range of agencies, from U.S. Fish and Wildlife Service, California State Fish and Game, to film and television companies, and the Monterey Bay Aquarium. He has an excellent reputation and decades of reliable performance. He's also fully equipped for over-water flights, a biologist by education himself, and he has done this very thing we will ask of him for the BBC.

Realistically, we can only put our operations into effect during good weather because we need to accomplish an unprecedented set of challenges on deck. For example, we plan to roll up alongside the whale so that its pectorals can be lashed in close to its flanks using a skiff. This allows us to tow the whale tail-first without hydrodynamic "porpoising" or spinning, etc., and, *very importantly*, without involving divers or swimmers, on the theory that sharks could be present at a dead whale carcass. We plan to focus any flights up the coast from Santa Cruz, where any carcass we are lucky enough to capture could be towed *downwind*, back into Monterey Bay. A Monterey Bay carcass would mean a less desirable upwind or crosswind tow, possibly of 25 or 30 miles *across* Monterey Bay. Our flights will most often take place near the coast, particularly during the northward migration of cows with calves. Flight time can also be used to check out a report of a dead whale before we put our complex (and more expensive) marine vessel operations into action.

Another detail of the plan is to put our own vessel and crew on standby for carefully selected, calm mornings and maximize our chances of a successful capture. That way, with some eyes-in-sky we will have narrowed the timing and conditions toward our own terms.

The point is that we would be *ready*, with the weather in our favor. We feel strongly that the aerial support will help maximize our efficiency and our chances of success; and even enhance the deck crews' safety (when you factor in the care we will put into launching the plane only on days chosen specifically for the safer sea conditions).

This year, we should have the opportunity to explore the procedures surrounding the bagging and towing operations. Still the efficiencies and safety elements make these tests more likely with some aerial support and we therefore place it higher on our list of priorities. These tests and opportunities to practice should actually improve our procedures using carefully selected support for safer on-the-water approaches to bagging and towing, a sufficient challenge for the upcoming northward springtime migration.

Phase 2 contains multiple steps:

Step 1 – How large a whale? We began thinking about the size of a whale that we might be able to handle by reading Perryman and Lynn (2002), a paper on gray whale condition using aerial photogrammetry. We figured that the absolute longest whale we would ever be able to handle would be 11.5 meters (38 ft.) and 2.4 m (8 ft.) wide. That size whale should still be narrow enough to fit in a cradle that can be pulled on the roadway without a special permit [maximum width = 2.6 m (102 inches) and maximum trailer length = 12.2 m (40 ft)]. Figure 7 from Perryman and Lynn (2002), suggests that about half the migrating whales would fit within our planned limits, except the widest southbound whales (pregnant females). Even though we have designed the equipment with those maximum values in mind, we would rather have a whale that is no more than 10.7 m (35 ft.) long and preferably less, particularly on our first attempt.

Capture and towing the whale carcass: Upon receipt of a dead whale report, we will deploy a suitable towing vessel with a specially designed, heavy-gauge body bag already onboard and stowed on a modified net reel. These pieces of equipment were designed and built last year in Phase 1.

Dr. David Casper of the Long Marine Lab Marine Mammal Stranding Network will supervise data collection during capture operations. We currently have permits to conduct these operations from the National Marine Fisheries Service and the Monterey Bay National Marine Sanctuary.

Captain Jim Christmann, RV Shana Rae and Monterey Canyon Research Vessels, will conduct and supervise all ocean operations. After proceeding to the site of the whale, we will tow the whale tail-first and winch the bag over the whale on a two-wire system (one winch and wire for the whale and one for the tow bag). In optimal weather conditions we plan to conduct this process entirely from the towing vessel, with an attendant skiff, but *without swimmers or divers in the water*. Excluding swimmers and divers is a precaution taken in case sharks are present and feeding on the carcass.

Oversized timber-handling “peavies” will be employed for the purpose of rolling the carcass as it lies alongside the fifty-foot towing vessel, so that pectoral fins can be secured along the specimen's flank and fastened all the way back to the caudal peduncle. This part of the process helps to preclude any unmanageable hydrodynamic effects from allowing the pectoral fins to trail freely in the water as the animal is towed tail-first.

Both the bag and the whale will be attached to separate tow lines and we do not anticipate having any trouble with the bag sinking since they will both be winched up tight to the boat. We specifically built the bag so that it was twice as long as we needed (70 ft.) in order to be able to influence the behavior of the bagged whale while under tow.

Cooling the carcass: The water volume in the bag could be brought down to 38 or 40 degrees during a multi-hour tow back to town, pushing it well below surface seawater temperature, partially as a result of the reduced volume of the winched bag and specimen. Once inside the harbor and haulout yard the whale can be winched into the cradle, where it fits more snugly into a new water-bath. This is why we designed tapered ends to the cradle with pre-cast foam inserts at the front of the cradle, the specimen's tail end. The reduced volume would minimize the volume of recirculating cold water, and the amount of weight to be transported. The cradle is sealed, hoisted from the harbor, and placed on the flatbed trailer on its way to a storage freezer and then to the CT scanner.

The end of a somewhat stiff section of cooling hose will be fashioned into a “shepherd's crook” or wishbone-shaped contrivance with its own degree of integrity. This will be inserted as far into the whale’s mouth as possible under admittedly uncertain sea surface conditions, and then secured along the specimen's length to a fixed point at the caudal peduncle, and part way up the towing wire to the vessel. Likewise, a section of the suction hose will be fixed to the caudal section, and led slightly forward along the specimen's flank with a large filter-body attached to it, so as to preclude debris from clogging the cooling system.

Dr. Krysl, a Professor of Engineering, used a thermal conductance value (0.18 watts/meter/°K), a value that was measured from bottlenose dolphin blubber and he scaled it up to gray whale size to figure out how long it would take to cool the largest whale carcass we would attempt to process. In the worst case scenario (largest whale), the central core of the whale would be within a couple of degrees of freezing after about a week. However, we also have plans to insert the output hose for the RSW system into the mouth of the whale when we begin the cooling process. This means that the structures in and around the head (including the ears) would be nearly frozen reasonably quickly, probably within a day or two, depending upon several factors. Some of these factors are: the power of the RSW system, the nutritive condition of the whale (blubber thickness), body length, the size of the pump and hoses on the RSW system, and others. Getting a better idea of the efficiency of this process will have to be done empirically. We think it is important to get the refrigeration system built as soon as possible so that we can use it to run some tests of cooling efficiency with a whale in the bag.

While at sea, we will have some control over the volume of water in the towed bag by winching as much of the front of the bag up and clear of the sea surface while simultaneously venting as much out the back as possible before closing the watertight Velcro and roll closure

Step 2: Once a freshly-killed whale carcass is successfully in the bag, the whole assembly would be winched up to within 3-5 meters of the towing vessel, where the RSW pressure hose, previously described, would be coupled to its counterpart coming from an on-deck, palletized, diesel-driven refrigeration system, and an appropriately sized suction hose coupled to it coming from the closed mouth of the bag. The back end of the bag will be tightly closed (astern of the specimen's head), and the bow end or mouth of the bag secured above the sea surface around the towing wire.

Both hoses will emerge from the closed bag, with the whale secure in a closed volume of isolated seawater. The refrigeration system will then be started and chilled seawater begins circulating out to the animal's mouth, emerging from around the anterior end and flowing inside the bag, toward the back of the bag. The hope is that this process will counteract as much of the heat of decomposition as possible and arrest as much of the decay process as possible; beginning perhaps within a couple or several hours of the animal's demise. Whether towing back to a chosen harbor takes 3 hours or 13 hours, this cooling process would have begun virtually as quickly as the freshly-killed specimen could be accessed, secured, bagged, and taken under tow.

Step 3: The cradle is designed to minimize the amount of water that could weight-shift or slosh around while on the road; and it is accordingly fitted with some adjustable foam inserts. Still, we need to have enough water to bathe the whale with the refrigerated water from the recirculating seawater (RSW) system. All equipment and apparatus construction will be carried out by David Jablonski at Sanctuary Stainless in Moss Landing, California.

Hoisting the whale (in the cradle) should not be a problem because the haul-out facilities on the Monterey Bay routinely handle heavier loads. The haulout yard in Moss Landing currently hauls a 55 ton steel troller, and the one in Santa Cruz has hauled the RV Shana Rae at about 35 tons.

When the towing vessel arrives at the haul-out yard with the whale in the bag, the cradle will be lifted off of the trailer and lowered into the water so that the whale in the bag can be winched directly into the cradle.

Step 4: It will not matter greatly if the flatbed/cradle assembly arrives at the chosen haul-out yard before or after the bagged whale is towed in, since the refrigeration system can continue to cool the whale, even overnight. If the towing vessel doesn't return to port until the nighttime hours, the bagged whale can be secured alongside the towing vessel. When the haul-out yard personnel arrive in the morning, they can clear their existing vessel-lifting commitments, and we can proceed once the tractor arrives with the flatbed/cradle assembly. These haul-out facilities routinely lift 40 and 50-foot vessels, so the whale should not provide any insurmountable handling difficulties.

The cradle will be lowered into the water with both ends open, and the bagged whale will be winched carefully into the submerged cradle after refrigeration hoses are disconnected. Then both ends of the cradle will be closed and sealed. The whale, in its chilled seawater bath-within cradled volume of harbor water, will never have lain flat on the deck of a vessel where internal organ structure might be compromised. Neither will it have rolled around in the surf on a rocky beach in the hot sun, but rather suspended in its chilled water bath, hopefully within hours of its death. This specimen will provide a unique window into the anatomy and physiology of baleen whales.

Step 5: Once the cradled carcass is safely chained down on its own fitted flatbed, the palletized refrigeration system can be transferred from the deck of the tow vessel to the flatbed trailer, and its hoses re-connected so the self-contained system can be re-started. Continuing to constantly cool the specimen can be resumed and maintained until the entire flatbed and cradle assembly is delivered to a pre-selected commercial freezer facility. The entire specimen can be frozen within its bag and eventually CT scanned without removing it from the cradle. Once the whale has been delivered to the freezer facility, the tractor operator can be released, until needed for subsequent transport to the industrial CT scanner at Hill AFB in Utah. At this point, most or all urgency will have been drained away from the project, so that the frozen specimen can be scheduled for transport to the X-ray CT facility when the scanner is available and it is convenient.

Upon arrival at the CT scanning facility, the cradle, which has been designed and built with this purpose in mind, could be slung and handled as it comes off the flatbed horizontally, or stood up vertically using suitably heavy lifting points at one end, and corresponding supporting feet on the other. After the CT scanning is complete, the specimen will be taken to the Smithsonian Institution in Washington D.C. where it will be carefully dissected and the tissue properties recorded for future modeling efforts. The skeleton of this valuable specimen will be housed in the collection at the Smithsonian.

We believe that this approach will provide the scientific community with the most carefully preserved young Gray Whale specimen ever examined. All of the components of the system (except the bag) are designed so that they are durable enough to be readily re-usable on any similarly-sized or smaller specimen if desirable. This strategy will severely bring down the costs of future efforts.

Video documentation has been ongoing throughout the life of the project. If we succeed in Phase 2, we will move on to Phase 3, building a finite element model. This effort will be described in a future proposal. This project will have demonstrated an innovative process that will serve the interest of the Navy, the public interest, and serve as a template for future studies. As a consequence, this project will likely revolutionize our understanding of the largest animals on Earth.

WORK COMPLETED

1. Conceptualized process of towing, bagging, refrigerating at sea, loading onto land, freezing, handling, and shipping of a young gray whale carcass to the scanning facility. Explored scientific relationships with MBARI and UCSC's Marine Mammal Stranding Network personnel, established the latter.

2. Built and field-tested a 1/25 scale model of the capture bag concept.

3. Designed, ordered, and accepted the full-scale towing bag from Seattle.

4. Located and modified hydraulic commercial gillnet reel for handling and storage of bag.

Figure 1. Rolling the tow bag onto the modified net reel.

5. Field tested the bag and reel assemblies for towing characteristics, modified as needed.

Figure 2. RV Shana Rae towing specially designed heavy-gauge bag that will contain the whale carcass.

6. Designed and assembled customized sling extensions, flensing knife, oversized log peavies for rolling a carcass into position for restraining pectoral fins, deck rollers for facilitating bag deployment. Acquired a clean, dry storage facility for bag and reel assemblies, and deposited them there for the off-season.

7. Established a working awareness of the project among local whale-watching vessels, and saw it proven out as incoming notice of a kill in May of 2011, and again in April of 2012. Close beach inspection of 23-foot gray whale carcass, with respect to towing and bagging considerations, May of 2011.

8. Established a working list of on-call deck volunteers to be able to respond to short-notice notification of a kill, and saw a successful assembly of capable individuals for a near-launch of a recovery effort, April, 2012. Also established a supportive relationship with a local, highly regarded aerial survey service with actual direct experience in locating gray whale / orca interactions for BBC film crews.

9. Refrigeration and freezing equipment design completed and ordered, and continuing refinement of designs for trucking and containment assemblies.

10. Establishing supportive relationships with the haulout facility, and possibly useful refrigeration for fisheries facilities, all in Moss Landing and all in touch with each other. This is a whole network of related businesses that might come into useful play during capture and processing operations.

RESULTS

Phase 2 of the project has been underway for less than six months. The results and accomplishments are contained in design, planning, preparation work that has already been completed.

IMPACT/APPLICATIONS

Navy sonar training operations have been hampered by concerns and lawsuits over the effects that high intensity sound exposure might have on marine organisms, specifically the mammals. Since the Navy has been tasked to understand any impact that its operations might have on living marine resources, it is important to work toward a methodology that will provide facts that will promote the assessment of vibroacoustic impact.

There is worldwide interest in the potential effects of anthropogenic sound on mysticete (baleen) whales. Most of the research on the effects of sound has been conducted on a few small marine mammal species that can be housed in research labs and aquaria but little is known about large marine mammals, like mysticetes. Long wavelength, low-frequency sounds are likely to have their most significant interaction with the bodies of these large animals. The large size of these animals precludes the potential to work with them in captivity in any meaningful way. Consequently, the most effective way to study the vibroacoustic physiology of these animals is to build a model of mysticete anatomy to study the interaction between these animals and low-frequency sound. Improvements in industrial-grade x-ray computed tomography (CT) scanners have made it feasible to scan an adult mysticete.

One viable method to assess exposure employs a computerized finite element modeling (FEM) environment to interrogate animal systems, increasing our understanding of how those systems work, testing the response of those systems to insult from high-intensity sounds, and assessing possible mitigation strategies prior to implementation. Producing this modeling environment is economical when compared to live animal work and provides a broad scope for investigation that cannot be matched or risked on live animals. Finally, the modeling environment allows investigators the flexibility to pivot quickly and nimbly to address inquiries of new claims or potential problems as they arise.

There is another realm of understanding that can be tapped by using FEM methods, but it might not be immediately obvious. The FEM tools allow us to conduct *virtual experiments*, a powerful but subtle capability. Consider the value of teasing apart the contributions of anatomic components in the formation of a sonar beam or the selective amplification function or filtering along the sound reception pathways. Our FEM tools could also be used to “test” selected changes to sonar signal characteristics or evaluate various mitigation strategies. The ability to conduct virtual experiments may prove to be the most powerful facet of the development of these FEM tools.

The success of this project will mark a sudden and conspicuous transformation in our understanding of the anatomy of mysticetes. To date, our knowledge of the whole-body anatomy of baleen whales has been largely based upon reports of centuries old dissections, using hand tools and draft animals with block and tackle, and from the whaling industry. It is a pity that the last published reference on systemic anatomy in baleen whales was by von Schulte in 1916, for a fetal fin whale.

There are two major advancements that accrue from capturing *in situ* anatomy in an adult mysticete as a means for understanding acoustic function: the geometry of anatomy and an advantageous

perspective. That is, the sizes, shapes and material composition of organs and tissue interfaces will determine their interaction with acoustic stimuli. In addition, it is very difficult to comprehend the anatomic structure of a mysticete by relying solely upon traditional dissection methods because the structures are much larger than the observer and any attempts to separate the slumping parts will all but destroy the indispensable anatomic geometry. These factors are currently unknown for any adult mysticete.

Modeling has several advantages. Models are flexible with respect to species and the variety of acoustic stimuli that can be tested. Once developed, models are also inexpensive to reuse in light of new information or apply to new questions. The models we propose to build are constructed at the organism level. This allows us to investigate interactions on the whole organism or to zoom in on structures or suites of structures to address questions of sound propagation and transmission across interfaces, distribution of acoustic pressure and shear stresses, dissipated energy and heating effects, excessive strains or displacements due to resonance, potential to induce cavitation, and other mechanical impacts.

This long-term, overarching research effort is robust and can be used to inform regulatory decisions about the effects of sounds on large marine mammals and/or fish.

RELATED PROJECTS

The current project, to CT scan an entire baleen whale and build a vibroacoustic model of it, is an outgrowth of an effort that was originally supported as a pilot project in 2004 by Dr. Frank Stone at the Chief of Naval Operations Environmental Readiness Division. That innovative project resulted in the *vibroacoustic toolkit* (VATk) and a number of published papers (Krysl *et al.*, 2006; Cranford *et al.*, 2007; McKenna *et al.*, 2007; Cranford *et al.*, 2008a; Cranford *et al.*, 2008b; Krysl *et al.*, 2008; Cranford *et al.*, 2010; McKenna *et al.*, 2011; Barroso *et al.*, 2012; Castellazzi *et al.*, 2012; Cranford and Krysl, 2012; Krysl *et al.*, 2012b). That success has led directly to an ongoing project to synthesize odontocete audiograms based upon the CT scanning and vibroacoustic modeling methodology we developed. We recently passed a significant milestone, validating the vibroacoustic modeling methodology by simulating sound production and beam formation in the bottlenose dolphin and matching it to previously published results with live dolphins (manuscript nearing completion).

A triple faceted project, *Virtual Experiments in Marine Bioacoustics: Whales, Fish, and Anthropogenic Sound*, was supported by an award from the Office of Naval Reseach, (N00014-09-1-0611). The **first** part of that project investigated whether our numerical vibroacoustic methodology could be applied to a completely different group of marine organisms. Experts have long puzzled over how fish discriminate the frequency and direction of progressive, relatively long wavelength sounds. Our research suggests that the three pairs of otholiths within their hearing apparatus actually "rock" in response to such sounds (Krysl *et al.*, 2012a; Schilt *et al.*, 2012). Rocking otoliths have important implications for our understanding of fish hearing, challenging long-standing traditional ideas. The **second** part of this multifaceted project includes an effort to build a portable device to measure elasticity and sound speed in excised tissue samples in a laboratory setting. A prototype has recently been built and we will test it at the Smithsonian Institution within days. The **third** and final aspect of this project proposes to validate our vibroacoustic models by comparing the simulation results to the psychoacoustic hearing experiments with live dolpins. The hearing experiments with the live dolphin were completed at the University of Hawaii in the past year. We are still involved in building the

vibroacoustic model so that we can run the corresponding numerical simulations. Until we have those simulation results, we will remain blind to the experimental outcomes with the Hawaiian dolphin.

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